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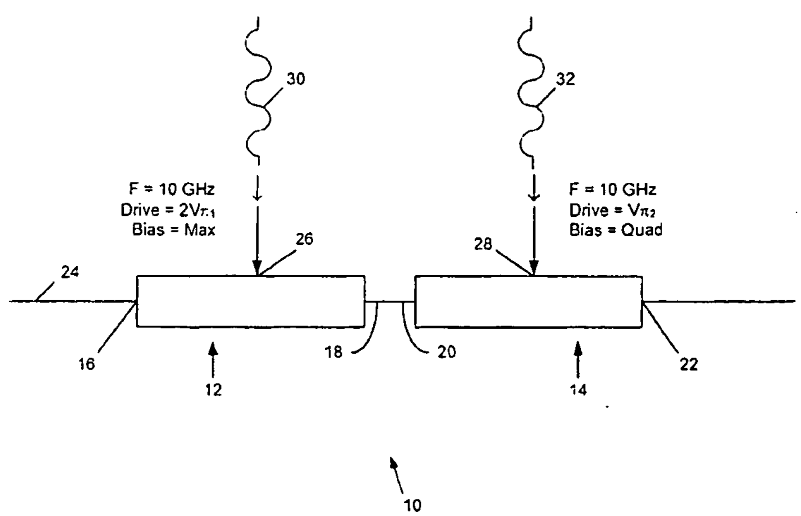
(54) **Title:** OPTICAL PULSE GENERATOR WITH SINGLE FREQUENCY DRIVE



(57) **Abstract:** An optical pulse generation system includes a first (12) and a second (14) optical interferometric modulator, each characterized by an optical output power - modulation voltage transfer function. A first drive signal (30) is applied to the first modulator, so as to modulate an input optical signal and provide a first modulated optical signal. A second drive signal (32) is applied to the second modulator, so as to modulate the first modulated optical signal. The bias voltage and the drive amplitude for the first drive signal are substantially different, compared to the bias voltage and drive amplitude for the second drive signal. The bias voltages and drive amplitudes of the drive signals can be chosen so as to generate output pulses having a relatively narrow pulse width (~16 ps), and a relatively high extinction ratio (~25 dB). The first and second drive signals are characterized by a substantially identical frequency (~10 GHz), permitting the system to use a relatively small number of commercially available parts.

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OPTICAL PULSE GENERATOR WITH SINGLE FREQUENCY DRIVE

Field of the Invention

The present invention relates to optical pulse generation, and in particular, to the generation of very narrow optical pulses for optical time-division multiplexed networks.

Background

The explosive growth in telecommunications and computer networking has led to an acute need for very high-bandwidth transmission systems. One approach to ultra-fast transmission is time-division-multiplexing (TDM) in all-optical networks, i.e. optical time-division-multiplexed (OTDM) networks.

Implementing the functional units constituting an OTDM network requires special considerations, because an OTDM network must have the capability of handling ultra-fast optical signals. In particular, very narrow optical pulses, with high repetition rates, must be generated, and these narrow optical pulses must be multiplexed and de-multiplexed. Narrow optical pulses are pulses that occupy very small intervals of time, or optical pulses that have a steep intensity change produced by a control signal. If the optical pulses are not narrow enough, the pulses would overlap within an optical channel, so that signal integrity in an OTDM network would be lost.

At high data rates, it is difficult to generate narrow optical pulses with prior art pulse generators, especially for very long distance propagation. Several methods have been used in the prior art to generate narrow and predetermined pulse formats. Some prior art methods include partially modulating the transfer function of a modulator with a device, such as an electro-absorption modulator, in order to generate fast pulses. In a prior art apparatus disclosed in U.S. Patent No. 4,505,587 issued to H.A. Haus et al. (the "'587 patent"), a set of cascaded Mach-Zehnder interferometers are used to generate optical pulses having a very narrow pulse width. In the '587 patent, input signals characterized by different and successively increasing frequencies are applied to each of a series of cascaded interferometers.

There are numerous disadvantages of these prior art designs. For example, a plurality of parts must be used, one for each drive frequency, adding to the physical size requirements for the device. Also, these prior art methods require precise control over the different input signals, which is both difficult and costly to achieve.

There is a need for an apparatus and method for generating very narrow optical pulses for modern optical communications systems, in particular for communications systems which

implement optical multiplexing. There also exists a need for generating pulses with a very narrow width that can be transmitted over long distances at high repetition rates. In particular, it is desirable to have an apparatus and method in which commercially available parts are used, in order to generate narrow optical pulses suitable for optical time-division multiplexed networks. It is also desirable to generate such narrow optical pulses using a relatively small number of commercially available parts. It is also desirable to generate narrow optical pulses characterized by relatively high extinction ratios.

Summary of the Invention

This invention relates to an optical pulse generation system and method, which can be implemented using a relatively small number of commercially available parts to generate very narrow optical pulses with a high extinction ratio, suitable for use in OTDM networks. In one embodiment of the invention, 16 ps pulses are generated at a 10 Gb/sec rate with a 25 dB extinction ratio. A principal discovery of the present invention is that ultra-short optical pulses characterized by a relatively narrow pulse width, as well as a relatively high extinction ratio, can be generated by driving a pair of cascaded interferometric modulators at substantially the same drive frequency (for example, a drive frequency within the RF band), and by selecting substantially different bias voltages and drive amplitudes for each modulator.

For each modulator, a bias voltage for the applied drive signal can be selected relative to the output power-modulation voltage transfer function of the modulator, and a corresponding drive amplitude established, in a way so as to substantially minimize the pulse width of the optical pulses, and in a way so as to substantially maximize the extinction ratio of the optical pulses generated by the optical pulse generation system. Both modulators are driven at the same frequency, in contrast to prior art methods in which drive signals characterized by different frequencies and centered around the same bias voltages (typically, at maximum optical transmission) are applied to each modulator.

An optical pulse generation system in accord with the present invention includes a first optical interferometric modulator and a second optical interferometric modulator. Preferably, the first and second interferometric modulators are Mach-Zehnder modulators. The optical output of the first interferometric modulator is coupled to the optical input of the second interferometric modulator. Each interferometric modulator includes a modulation input for receiving a modulation voltage drive signal that modulates an optical signal that has been received in the optical input of the modulator.

Each interferometric modulator is characterized by an optical output power-modulation

voltage transfer function. In an exemplary embodiment, the modulator transfer function of each modulator is a "raised cosine" type transfer function. In a preferred embodiment of the invention, the first modulator is characterized by a parameter $V\pi_1$ representing the voltage required to change the output power from the first modulator from a minimum value to a maximum value, and the second modulator is similarly characterized by a parameter $V\pi_2$ representing the voltage required to change the output power from the second modulator from a minimum value to a maximum value.

The optical pulse generation system includes means for applying a first modulation voltage drive signal to the modulation input of the first modulator, and means for applying a second modulation voltage drive signal to the modulation input of the second modulator. The first drive signal is characterized by a first bias voltage normalized to $V\pi_1$, an amplitude A1 normalized to $V\pi_1$, and a frequency F1. The first drive signal modulates an input optical signal received by the optical input of the first modulator about the first bias voltage, with the normalized amplitude A1. A first modulated optical signal is thereby generated from the output of the first modulator.

Similarly, the second drive signal is characterized by a second bias voltage normalized to $V\pi_2$, an amplitude A2 normalized to $V\pi_2$, and a frequency A2. The second drive signal modulates the first modulated optical signal, received by the optical input of the second modulator, about the second bias voltage with the normalized amplitude A2. The optical output of the second modulator provides a second modulated optical signal in the form of optical pulses. Because the second modulator is cascaded to the first modulator, the output optical pulses generated by the optical pulse generation system of the present invention are substantially equal to the product of the pulses produced by the first modulator, and the pulses that would nominally be produced by the second modulator if the optical signal received at the input of the second modulator were characterized by an output power constant in time.

In one embodiment of the invention, the first and second bias voltages, and the first and second drive amplitudes, are chosen so as to substantially minimize the pulse width of the output optical pulses generated by the optical pulse generation system. In this embodiment, output optical pulses of about 16 ps are generated at 10 Gb/sec with an extinction ratio of about 20 dB. In this embodiment, the first bias voltage biases the first interferometric modulator substantially at the maximum optical transmission. The second bias voltage biases the second interferometric modulator substantially at quadrature, i.e. at the half-power point. The corresponding drive amplitude for the first drive signal is about twice $V\pi_1$, and the corresponding drive amplitude for the second drive signal is about $V\pi_2$. In this exemplary embodiment, the identical drive

frequencies F1 and F2 are in the RF band, and are about 10 GHz.

In another embodiment of the invention, the first and second bias voltages, and the first and second drive amplitudes, are chosen so that the output optical pulses generated by the optical pulse generation system of the present invention are characterized by a relatively high extinction ratio, i.e. a highly suppressed side lobe energy. In this embodiment, the first bias voltage biases the first interferometric modulator at a maximum optical transmission, and the second bias voltage biases the second interferometric modulator at about 130 degrees relative to the maximum optical transmission. The drive amplitude for the first drive signal is about twice $V\pi_1$, and the drive amplitude for the second drive signal is about (0.6) * $V\pi_2$. Both signals have a frequency of about 10 GHz. The resulting output pulses have a pulse width of about 16 ps, a repetition rate of 10 Gb/sec, and an extinction ratio of about 25 dB.

The present invention features a method of generating optical pulses. The method includes generating a first modulated optical signal by applying a first modulation drive signal to a first optical interferometric modulator, so as to modulate an input optical signal (for example provided by a CW laser source) received into the modulator. The method includes generating a second modulated optical signal, in the form of narrow optical pulses, by applying a second modulation voltage drive signal to a second optical interferometric modulator so as to modulate the first modulated optical signal. The first and second drive signals are characterized by substantially different bias voltages and drive amplitudes, and by a substantially identical drive frequency. The method includes varying the bias voltages and the drive amplitudes so as to substantially minimize the pulse width of optical pulses in the second modulated optical signal. The method includes varying the bias voltages and the drive amplitudes so as to substantially maximize the extinction ratio of the optical pulses in the second modulated optical signal.

Brief Description of the Drawings

Fig. 1 illustrates an optical pulse generation system constructed in accordance with one embodiment of the present invention. Cascaded first and second interferometric modulators, are driven with bias and drive conditions chosen so as to generate output optical pulses having a relatively narrow pulse width.

Fig. 2 illustrates a Mach-Zehnder interferometric modulator, as known in the prior art.

Fig. 3A illustrates the modulator transfer function for the first interferometric modulator, driven with a drive signal biased at the maximum optical output power, and having a drive amplitude of twice $V\pi_1$.

Fig. 3B illustrates the modulator transfer function for the second interferometric

modulator,

driven with a drive signal biased at quadrature, and having a drive amplitude of $V\pi_2$.

Fig. 4 illustrates the output optical signals from the first and second interferometric modulators, for the bias and drive conditions shown in Fig.s 3A and 3B.

Fig. 5 illustrates the output optical pulses from an optical pulse generation system having the bias and drive conditions shown in Fig.s 3A and 3B.

Fig. 6 illustrates on a log scale the output optical pulses from an optical pulse generation system having the bias and drive conditions shown in Fig.s 3A and 3B.

Fig. 7 illustrates another embodiment of an optical pulse generation system in accordance with one embodiment of the present invention, in which the bias and drive conditions are chosen so as to generate optical pulses having a relatively high extinction ratio, namely about 25 dB, and a pulse width of about 16 ps.

Fig. 8A illustrates the modulator transfer function and the bias and drive conditions for the first interferometric modulator, in an embodiment of the invention in which the bias voltages and the drive amplitudes are chosen so as to generate optical pulses having a relatively high extinction ratio.

Fig. 8B illustrates the modulator transfer function and the bias and drive conditions for the second interferometric modulator, in an embodiment of the invention in which the bias voltages and the drive amplitudes are chosen so as to generate optical pulses having a relatively high extinction ratio.

Fig. 9 illustrates the output optical signals from the first and second interferometric modulators, for the bias and drive conditions shown in Fig.s 8A and 8B.

Fig. 10 illustrates the extinction ratio of the output pulses when the bias voltages and the drive amplitudes are chosen as illustrated in Fig. 8A and 8B.

Detailed Description

The present invention allows for the generation of pulses having a relatively narrow pulse width, and a relatively low duty cycle, for example 16%. A low duty cycle allows for optical time division multiplexing (OTDM) to be accomplished in a relatively simple way. For high-speed OTDM transmission, an optical pulse must be very narrow. This is because a single clock pulse is split into multiple channels, depending on the ratio by which the data transmission rate of a single channel is to be enhanced through optical multiplexing. The optical pulses in all of the channels are optically modulated, in parallel. The optical pulse outputs from the multiple channels are then combined together, resulting in an optically multiplexed OTDM signal. The

original clock pulses must thus be narrow enough so as to avoid overlapping within a single channel. In particular, for high bandwidth optical communications networks it is desirable that optical pulses be narrow enough to fit into a single channel having a bandwidth of at least 40 Gb/sec or higher. The present invention provides a relatively simple and low cost system and method for generating narrow optical pulses needed for OTDM systems.

In the present invention, a pair of cascaded optical interferometric modulators are driven with modulation voltage drive signals. Each interferometric modulator is driven at substantially the same frequency, for example at about 10 GHz, although other frequencies are also within the scope of this invention. Each modulator is driven about substantially different bias voltages, and with substantially different drive amplitudes. The bias voltages and the drive amplitudes of the modulation drive signals for each modulator are varied so as to generate output optical pulses having a desired pulse width, and a desired extinction ratio. In particular, the bias and drive conditions may be chosen so as to substantially minimize the pulse width and substantially maximize the extinction ratio of the output optical pulses, in a preferred embodiment of the invention. Using a single drive frequency for both modulators allows narrow optical pulses to be generated while using a relatively small number of commercially available parts.

Fig. 1 illustrates one embodiment of an optical pulse generation system 10, constructed in accordance with the present invention. In this embodiment, the bias and drive conditions for each of a pair of cascaded interferometric modulators are chosen so as to generate output optical pulses having a relatively narrow pulse width, namely about 16 ps. The system 10 includes a first optical interferometric modulator 12 and a second optical interferometric modulator 14. Optical interferometric modulator 12 includes an optical input 16 for receiving an optical input signal, and an optical output 20 for providing a first optical output signal. Similarly, optical interferometric modulator 14 includes an optical input 18 for receiving an optical input signal and an optical output 22 for providing a second optical output signal. The optical output 20 of the first interferometric modulator 12 is coupled to the optical input 18 of the second interferometric modulator 14. The optical input signal received by the optical input 16 of the first interferometric modulator is generated by a source (not shown) of optical radiation, preferably a CW (continuous wavelength) laser, and is transmitted through an optical delivery structure, such as an optical fiber 24.

Each optical interferometric modulator includes a modulation input (26 and 28) for receiving a first modulation voltage drive signal 30 and a second modulation voltage drive signal 32, respectively. Each optical interferometric modulator may also include bias means for biasing the first and second drive signals. Each optical interferometric modulator is characterized by a

modulator transfer function, which defines the optical output power from the modulator as a function of the applied modulation voltage. The first interferometric modulator 12 and its modulator transfer function are characterized by a parameter $V\pi_1$, representing the voltage required to change the optical output power from the first modulator 12 from a minimum value to a maximum value. Similarly, the second interferometric modulator 14 and its transfer function are characterized by a parameter $V\pi_2$, representing the voltage required to change the optical output power from the second modulator 14 from a minimum value to a maximum value.

In the present invention, the first modulation drive signal 30 and the second modulation voltage drive signal 32 have substantially the same frequency. In the illustrated embodiment, the drive frequency is about 10 GHz, although other drive frequencies (for example 20 GHz) are also within the scope of the present invention. A single 10 GHz oscillator can thus be used in the illustrated embodiment of the invention, in order to generate both drive signals. From the viewpoint of practical implementation, a single frequency drive thus permits the system 10 to minimize the number of commercially available parts necessary to generate narrow optical pulses, as mentioned earlier. This is in contrast to prior art pulse generators using cascaded Mach-Zehnder interferometers, in which each interferometer is driven at different frequencies, for example harmonically related frequencies.

As indicated in Fig. 1, the first interferometric modulator 12 is driven with a first modulation drive signal 30 which is applied to the modulation input 26. The modulation drive signal 30 is biased at the transfer function maximum, i.e. centered about a bias voltage chosen to correspond to the modulation drive voltage at which the output optical power from the first interferometric modulator 12 has a peak value. As indicated in Fig. 1, the RF drive amplitude for the first modulator is chosen to be twice $V\pi_1$. The second modulator is driven with a second modulation drive signal 32 which is applied to the modulation input 28. The modulation drive signal 32 is biased at quadrature, i.e. is centered about a bias voltage corresponding to the modulation drive voltage at which the output optical power from the second interferometric modulator 14 is one half the peak value. The RF drive amplitude for the second modulator is chosen to be equal to $V\pi_2$.

In a preferred embodiment, the first 12 and second 14 optical interferometric modulators are Mach-Zehnder modulators. Fig. 2 illustrates a Mach-Zehnder interferometric modulator 100, known in the prior art. In a Mach-Zehnder interferometer, an incoming optical signal 102 is split at a Y-junction into two signals, E_1 and E_2. Each signal enters a first waveguide branch 104 and a second waveguide branch 106, respectively. The signals are recombined into an output waveguide 110, which provides a modulated optical output signal, E_3.

Preferably, the Mach-Zehnder modulator 100 is formed on a lithium niobate substrate. Because of its high electro-optic coefficient, lithium niobate provides an efficient means of achieving optical modulation. Because lithium niobate is optically active, the index of refraction of a waveguide region can be altered by applying an electric field in that region. Typically, a modulation signal 107 is applied to a modulator input electrode 108. The signal 107 causes an electric field to be applied to one or both of the waveguide branches 104 and 106.

In accordance with the electro-optic effect, an electric field applied to a waveguide branch causes the index of refraction in the waveguide branch to change with the changing amplitude of the modulating signal. The change in the index of refraction alters the speed (or phase) of light in the region, resulting in a change in the delay time of the light passing through the region. The modulation signal thus enables the optical path length in one or both of the waveguide branches to be controlled, and a phase difference results between the two signals E_1 and E_2, when they are recombined at the output waveguide 110. The interference of the two recombined signals results in an intensity modulated output signal E3.

Fig. 3A graphically illustrates the modulator transfer function 200 for the first interferometric modulator, as well as the bias and drive conditions for the first modulation voltage drive signal 30. As seen from Fig. 3, the modulator transfer function 200 is a periodic function of drive voltage in the illustrated embodiment. The transfer function 200 preferably has a "raised cosine" sinusoidal form, although other periodic forms of the transfer function 200 are also within the scope of the present invention. In the illustrated embodiment, the modulator transfer function 200 is symmetrical about a center voltage V_{10} between a lower drive voltage V_{1-} and an upper drive voltage V_{1+}, and is substantially a single period sinusoid, as a function of drive voltage, between V_{1-} and V_{1+}. The modulator transfer function 200 has a maximum value at V_{10}, and a minimum value at V_{1-} and at V_{1+}.

As illustrated in Fig. 3A, the first drive signal 30 is a periodic function of time with a frequency F1 and a peak-to-peak amplitude A1, normalized to $V\pi_1$. In the illustrated preferred embodiment of the invention, the first drive signal 30 is a sinusoidal function of time. In other embodiments, however, the first drive signal 30 may be represented by periodic functions of time other than sinusoidal functions. By way of example, the first drive signal 30 may be a square wave signal. The first drive signal 30 causes time-varying, oppositely directed electric fields to be applied to the two waveguide branches of the first Mach-Zehnder modulator. In a preferred form of the present invention, the frequency F1 of the first modulation drive signal 30 is in the RF range, about 10 GHz, but other frequencies may be used in other embodiments of the invention. The first drive signal 30 is centered about a first bias voltage $V1 = V_{1-} + V_{1B}$, where

V_{1B} is a voltage magnitude normalized to $V\pi_1$. In the embodiment illustrated in Fig. 3A, V_{1B} is equal to $V\pi_1$. The first bias voltage V1 biases the first modulator at the maximum optical transmission, so that V1 happens to be equal to V_{10}. The corresponding peak-to-peak drive amplitude A1 has a magnitude of two times $V\pi_1$, or $(V_{1+} - V_{1-})$.

Fig. 3B illustrates the modulator transfer function 300 for the second interferometric modulator, in the embodiment of the invention illustrated in Fig. 1, as well as the bias and drive conditions for the second drive signal 32. Preferably, the modulator transfer function 300 is substantially identical to the modulator transfer function 200 (shown in Fig. 3A).

In the illustrated embodiment, the modulator transfer function 300 is also symmetrical about a center voltage V_{20} between a lower drive voltage V_{2-} and an upper drive voltage V_{2+}, and is substantially a single period sinusoid, as a function of drive voltage, between V_{2-} and V_{2+}. The modulator transfer function 300 has a maximum value at V_{20}, and a minimum value at V_{2-} and at V_{2+}.

In the illustrated embodiment, the second drive signal 32 is a sinusoidal function of time, with a frequency F2 and a peak-to-peak amplitude A2. However, in other embodiments of the invention the second drive signal 32 may be represented by periodic functions of time other than sinusoidal functions, including but not limited to square wave functions. The second drive signal 32 also causes time-varying, oppositely directed electric fields to be applied to the two waveguide branches of the second Mach-Zehnder modulator. The second modulation drive signal 32 is centered about a second bias voltage $V2 = V_{2-} + V_{2B}$, where V_{2B} is a voltage magnitude normalized to $V\pi_2$. In the embodiment illustrated in Fig. 3B, V_{2B} is $(1/2) * V\pi_2$, and the second bias voltage V2 biases the second modulator at quadrature, i.e. at the half-power point. The corresponding peak-to-peak drive amplitude A2 has a magnitude of $V\pi_2$, or $(V_{2+} - V_{2-}) / 2$. The second bias voltage V2 may also be expressed in terms of V_{2+} and V_{2-}: $V2 = (1/4) * (V_{2+} - V_{2-}) + V_{2-}$.

In operation, an input optical signal is generated by an optical source (not shown), preferably a CW (continuous wavelength) laser. The modulation driver, or other means for applying a drive signal, applies the first drive signal 30 to the modulation input of the first interferometric modulator 12. The first drive signal 30 modulates the input optical signal, so that a first modulated optical signal 400 is generated by the first interferometric modulator. The first modulated optical signal 400 is composed of RZ (return-to-zero) optical pulses. By driving the first modulator at 10 GHz with a bias at the maximum optical transmission, the frequency of the optical pulses is doubled, effectively reducing the pulse width. As a result, the modulated optical signal 400 from the output of the first modulator consists of a 20 Gb/sec train of optical pulses,

having a pulse width of ~ 16 ps. The modulated optical signal 400 is received into the optical input of the second modulator. The second modulation voltage drive signal 32 is applied to the modulation input of the second modulator. The second drive signal 32 modulates the first modulated optical signal 400 about the second bias voltage, i.e. at quadrature, with the second normalized drive amplitude A2 that is equal to one half of $V\pi_2$.

Fig. 4 illustrates the output optical signals from the first interferometric modulator and the second interferometric modulator, for the bias and drive conditions shown in Fig.s 3A and 3B. The solid curve illustrates the modulated optical signal 400 generated from the first modulator. The dashed curve 410 illustrates the pulses that nominally would result, assuming a constant input optical power at the optical input 16, when the second modulator is driven with the second modulation drive signal 32 (shown in Fig. 3B), at a drive amplitude of $V\pi_2$ and a bias voltage at quadrature or half power point. A second set of pulses, i.e. a 10 Gb/sec train of pulses would nominally be generated by the second interferometric modulator, having a pulse width of ~ 50 ps. However, since the optical signal received at the input of the second modulator is not constant, but rather has the time varying modulated output of the first interferometric modulator, the second stage in effect gates the pulses from the first stage to provide, at the optical output 22, a 10 Gb/sec stream of 16 ps pulses.

Fig. 5 illustrates the output optical pulses 500 generated by the optical pulse generation system 10 constructed in accordance with the present invention. The pulses from the second interferometric modulator perform a gating function on the optical signals that are received by the optical input of the second interferometric modulator. The result is that every other pulse, from the first set of pulses generated by the first interferometric modulator, is gated out. A small amount of residual side lobe power 510 is visible, where every other pulse has been gated out, as a result of applying the second drive signal to the second interferometric modulator.

The residual side lobe energy is more easily observed on a log scale, shown in Fig. 6. The amplitudes of the side lobes 510 are shown in units of dB, on a log scale. It can be seen from Fig. 6 that the side lobes 510 of optical power have amplitudes that are about 20 dB lower, as compared to the amplitudes of the main pulses 500.

This residual power causes coherent interference, when the pulses are optical time-division multiplexed to 20 Gb/sec rates. It is desirable to minimize leakage power, because such coherent interference reduces the link margin. In addition to leakage caused by the side lobes, there may be additional leakage due to imperfect extinction in the lithium niobate interferometric modulator. A seemingly negligible amount of side lobe energy can result, after optical multiplexing, in substantial fluctuations in optical power. Side lobe energy of the order of only

1-2 % can create up to 40 % fluctuations in optical power, when the pulse stream illustrated in Fig. 5 is optically multiplexed. It is therefore desirable to lower the side lobe energy, i.e. maximize the extinction ratio of the optical pulses.

In the present invention, parameters including the pulse width and the extinction ratio are optimized by varying the bias and drive conditions of the first and second drive signals. In particular, the bias voltages and drive amplitudes for the first and second interferometric modulators can be varied so as the change and/or substantially minimize the pulse width of the output optical pulses, as described in relation to the embodiment illustrated in Figs. 1 and 3-5. In other embodiments of the invention, the bias voltages and the drive amplitudes for the first and second interferometric modulators may be varied so as to achieve a desired extinction ratio for the output optical pulses.

Fig. 7 illustrates another exemplary embodiment of an optical pulse generation system 10 constructed in accordance with the present invention, in which the bias and drive conditions are chosen so as to generate optical pulses having a relatively high extinction ratio, namely about 25 dB, and having a pulse width of about 16 ps. As seen from Fig. 7, the increase in extinction ratio is achieved by moving the bias point of the second interferometric modulator from the quadrature point (at 90 degrees with respect to the maximum optical transmission) towards the null, i.e. towards the minimum optical transmission, which is located at 180 degrees with respect to the maximum optical transmission. The bias point is moved from the quadrature point by about 40 degrees, to a bias point located at about 130 degrees relative to the maximum optical transmission. The drive amplitude for the second drive signal is lowered to less that $V\pi_2$, to about (0.6) * $V\pi_2$.

Fig.s 8A and 8B illustrate the modulator transfer function and the bias and drive conditions for the first and the second interferometric modulators, in an embodiment of the invention in which the bias voltages and the drive amplitudes are chosen so as to generate optical pulses having a relatively high extinction ratio. Also shown are a first drive signal 600 applied to the first modulator, and a second drive signal 610 applied to the second modulator. In this embodiment, the first modulator is biased at maximum, and driven with a 2 * $V\pi_1$ amplitude, as in the case illustrated in Figs. 3A and 3B. The second modulator is driven very low, with a drive amplitude of about (0.6) * $V\pi_2$ and the bias point chosen near null, namely at about 130 degrees with respect to the maximum optical transmission.

Fig. 9 illustrates the output optical signals from the first and second interferometric modulators, for the bias and drive conditions shown in Fig.s 8A and 8B. The solid curve 700 illustrates the optical pulses generated from the output of the first modulator when driven with

the drive signal 600. These optical pulses are a 20 Gb/sec train of 16 ps optical pulses, as described earlier. The dashed curve 710 illustrates the pulses that nominally would result, if a constant input optical power were received into the optical input of the second modulator, and if the second modulator were driven with the second drive signal 610, biased near null at 130 degrees from the maximum, and with a drive amplitude of 0.6 * $V\pi_2$. A 10 Gb/sec train of pulses having a pulse width of 50 ps, illustrated in Fig. 9 as the dashed curve 610, would nominally be generated. The maximum pulse height for these pulses would be slightly over 60% of the pulses generated from the output of the first modulator. As explained earlier, the second modulator effectively gates the pulses from the first modulator, so that the output optical pulses from the optical pulses generation system are a product of the first set of optical pulses from the first modulator, and the second set of pulses generated by the second modulator.

The output pulse train is illustrated in Fig. 10, on a log scale. Fig. 10 illustrates the suppression of side lobe energy when the bias voltages and the drive amplitudes are chosen according to the conditions shown in Figs. 8A and 8B, so as to generate output optical pulses having a relatively high extinction ratio. Fig. 10 shows the main output pulses 800 and the side lobes 810, as a function of time. The amplitudes of the main pulses 800 and the side lobes 810 are shown in units of dB. It can be seen that the residual power is about 7 dB lower, as compared to Fig. 6, which illustrates the case in which a first modulator driven at a maximum bias with a 2 $V\pi_1$ amplitude is cascaded to a second modulator driven at quadrature with a $V\pi_2$ amplitude. However, the peak amplitude of the main pulses 800 for the embodiment illustrated in Fig. 10 is about 2 dB lower, as compared to the peak amplitude of the main pulses 500 for the embodiment illustrated in Fig. 6. An improvement of about 5 dB is therefore achieved, as compared to the embodiment illustrated in Fig. 6.

While the invention has been particularly shown and described with reference to specific preferred embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims.

CLAIMS

1. An optical pulse generation system, comprising:

A. a first optical interferometric modulator having:

i. an optical input for receiving an optical input signal,

ii. a modulation input for receiving a first modulation voltage drive signal that modulates said optical input signal;

iii. an optical output for providing a first modulated optical signal;

wherein said first interferometric modulator is characterized by an optical output power-modulation voltage transfer function, and a parameter $V\pi_1$ that represents the voltage required to change the output power from the first modulator from a minimum value to a maximum value; and

wherein said transfer function of said first modulator is symmetrical about a center voltage between a lower drive voltage V_{1-} and an upper drive voltage V_{1+}, having a maximum optical output power at the center voltage, and a minimum optical output power at V_{1-} and at V_{1+}, and

B. a second optical interferometric modulator having:

i. an optical input for receiving said first modulated optical signal,

ii. a modulation input for receiving a second modulation voltage drive signal that modulates said first modulated optical signal

iii. an optical output for providing a second modulated optical signal;

wherein said second optical interferometric modulator is characterized by an optical output power-modulation voltage transfer function, and a parameter $V\pi_2$ that represents the voltage required to change the output power from the first modulator from a minimum value to a maximum value; and

wherein said transfer function of said second optical interferometric modulator is symmetrical about a second center voltage between a lower drive voltage V_{2-} and an upper drive voltage V_{2+}, having a maximum optical output power at the second center voltage, and a minimum optical output power at V_{2-} and at V_{2+};

C. a first modulator driver for applying said first modulation voltage drive signal to said modulation input of said first modulator,

wherein said first modulation voltage drive signal is a periodic function of time having a frequency F1, and having a peak-to-peak amplitude A1 normalized to $V\pi_1$, and is centered about a first bias voltage $V1 = V_{1-} + V_{1B}$, wherein V_{1B} is a voltage magnitude normalized to $V\pi_1$;

and

D. a second modulator driver for applying said second modulation voltage drive signal to said modulation input of said second modulator,

wherein said second modulation voltage drive signal is a periodic function of time having a frequency F2, and having a peak-to-peak amplitude A2 normalized to $V\pi_2$, and is centered about a second bias voltage $V2 = V_{2-} + V_{2B}$, wherein V_{2B} is a voltage magnitude normalized to $V\pi_2$;

and

wherein F1 substantially equals F2.

2. A system according to claim 1, wherein V1 and V2 are substantially different.

3. A system according to claim 1, wherein at least one of the first bias voltage and the second bias voltage is selected so that the optical pulses in the second modulated signal have a predetermined pulse width.

4. A system according to claim 3, wherein said predetermined pulse width is about 16 ps.

5. A system according to claim 3, wherein V_{1B} has a magnitude of about $V\pi_1$, and said first bias voltage V1 biases the first interferometric modulator substantially at a maximum optical transmission; and

wherein V_{2B} has a magnitude of about one half $V\pi_2$, and said second bias voltage V2 biases the second interferometric modulator substantially at quadrature.

6. A system according to claim 1, wherein said amplitude A1 for said first drive signal is substantially different from said amplitude A2 for said second drive signal.

7. A system according to claim 1, wherein said amplitude A1 for said first drive signal is substantially twice $V\pi_1$, and wherein said amplitude A2 for said second drive signal is substantially $V\pi_2$.

8. A system according to claim 1, wherein F1 and F2 are about 10 GHz.

9. A system according to claim 1, wherein the second modulated optical signal comprises

RZ optical pulses.

10. A system according to claim 9, wherein the pulse rate of said output optical pulses is about 10 Gb/sec.

11. A system according to claim 1, wherein at least one of the first and second interferometric modulators comprises a Mach-Zehnder modulator.

12. A system according to claim 1, wherein at least one of the first bias voltage and the second bias voltage is selected so that the optical pulses in the second modulated signal have a predetermined extinction ratio.

13. A system according to claim 12, wherein said predetermined extinction ratio is from about 25 dB to about 30 dB.

14. A system according to claim 12, wherein said first bias voltage V_{1B} biases the first interferometric modulator at a maximum optical transmission; and

wherein said second bias voltage V_{2B} biases the second interferometric modulator at about 130 degrees with respect to the maximum optical transmission.

15. A system according to claim 12, wherein said amplitude A1 for said first drive signal is twice $V\pi_1$, and wherein said amplitude A2 for said second drive signal is substantially (0.6) * $V\pi_2$.

16. An optical pulse generation system, comprising:

A. a first optical interferometric modulator having:

i. an optical input for receiving an optical input signal,

ii. a modulation input for receiving a first modulation voltage drive signal that modulates said optical input signal;

iii. an optical output for providing a first modulated optical signal;

wherein said first interferometric modulator is characterized by an optical output power-modulation voltage transfer function; and

wherein said transfer function of said first modulator is symmetrical about a center voltage V_{10} between a lower drive voltage V_{1-} and an upper drive voltage V_{1+}, and is

substantially a single period sinusoid as a function of drive voltage between V_{1-} and V_{1+}, having a maximum value at V_{10}, and a minimum value at V_{1-} and at V_{1+}, and

B. a second optical interferometric modulator having:

i. an optical input for receiving said first modulated optical signal,

ii. a modulation input for receiving a second modulation voltage drive signal that modulates said first modulated optical signal

iii. an optical output for providing a second modulated optical signal;

wherein said second optical interferometric modulator is characterized by an optical output power-modulation voltage transfer function;

wherein said transfer function of said second optical interferometric modulator is symmetrical about a second center voltage V_{20} between a lower drive voltage V_{2-} and an upper drive voltage V_{2+}, and is substantially a single period sinusoid as a function of drive voltage between V_{2-} and V_{2+}, having a maximum value at V_{20}, and a minimum value at V_{2-} and at V_{2+};

C. a first modulator driver for applying said first modulation voltage drive signal to said modulation input of said first modulator,

wherein said first modulation voltage drive signal is a periodic function of time having a frequency F1, and having a peak-to-peak amplitude A1, and is centered about a voltage V1;

and

D. a second modulator driver for applying said second modulation voltage drive signal to said modulation input of said second modulator,

wherein said second modulation voltage drive signal is a periodic function of time having a frequency F2, and having a peak-to-peak amplitude A2, and is centered about a second voltage V2;

and

wherein F1 substantially equals F2.

17. A system according to claim 1, wherein:

$A1 = (V_{1+} - V_{1-})$;

$V1 = V_{10}$;

$A2 = (V_{2+} - V_{2-}) / 2$; and

$V2 = (1/2) * [(V_{2+} - V_{2-}) / 2] + V_{2-}$

18. An optical pulse generation system comprising:

A. a first interferometric modulator, said first interferometric modulator comprising:

i. an optical input for receiving an input optical signal;

ii. at least one electrical input for receiving a first electrical signal, the first electrical signal being characterized by a first normalized bias voltage and a first periodic waveform, the first electrical signal modulating the input optical signal about the first bias voltage with a first normalized amplitude;

iii. an optical output that provides a first modulated optical signal; and

B. a second interferometric modulator comprising:

i. an optical input for receiving the first modulated optical signal;

ii. at least one electrical input for receiving a second electrical signal, the second electrical signal being characterized by a second normalized bias voltage and a second periodic waveform, the second electrical signal modulating the first modulated optical signal about the second normalized bias voltage with a second normalized amplitude;

iii. an optical output that provides a second modulated optical signal comprising optical pulses;

wherein the first normalized bias voltage and the second normalized bias voltage are substantially different.

19. A system according to claim 18, wherein the first periodic waveform and the second periodic waveform are characterized by substantially the same frequency.

20. A system according to claim 18, wherein the first periodic waveform and the second period waveform are substantially sinusoidal waveforms.

21. An optical pulse generation system comprising:

A. a first interferometric modulator, said first interferometric modulator comprising:

i. an optical input for receiving an input optical signal;

ii. at least one electrical input for receiving a first electrical signal, the first electrical signal being characterized by a first normalized bias voltage and a first periodic waveform, the first electrical signal modulating the input optical signal about the first bias voltage with a first normalized

amplitude;

iii. an optical output that provides a first modulated optical signal; and

B. a second interferometric modulator comprising:

i. an optical input for receiving the first modulated optical signal;

ii. at least one electrical input for receiving a second electrical signal, the second electrical signal being characterized by a second normalized bias voltage and a second periodic waveform, the second electrical signal modulating the first modulated optical signal about the second normalized bias voltage with a second normalized amplitude;

iii. an optical output that provides a second modulated optical signal comprising optical pulses;

wherein the first and the second periodic waveform have substantially the same frequency.

22. An optical pulse generation system according to claim 21, further comprising:

a. means for applying said first electrical signal to said at least one electrical input of said first interferometric modulator, and

b. means for applying said second electrical signal to said at least one electrical input of said second interferometric modulator.

23. An optical pulse generation system according to claim 21, further comprising bias means for biasing said first and second electrical signals.

24. A method of generating optical pulses, the method comprising:

A. generating a first modulated optical signal comprising optical pulses by applying a first modulation voltage drive signal to a modulation input of a first optical interferometric modulator so as to modulate an input optical signal that has been received into an optical input of said first interferometric modulator, said first modulation voltage drive signal being characterized by a first normalized bias voltage and a first periodic waveform having a first normalized amplitude;

B. generating a second modulated optical signal comprising optical pulses by applying a second modulation voltage drive signal to a modulation input of a second optical interferometric modulator so as to modulate the first modulated optical signal with a second modulation voltage drive signal characterized by a

second normalized bias voltage and a second periodic waveform having a second normalized amplitude;

wherein the first periodic waveform and the second periodic waveform are characterized by a substantially identical frequency.

25. A method according to claim 24, wherein the first normalized bias voltage and the second normalized bias voltage are substantially different.

26. A method according to claim 24, further comprising varying at least one of the first normalized bias voltage and the second normalized bias voltage to substantially minimize pulse width of optical pulses in the second modulated optical signal.

27. A method according to claim 24, further comprising varying the first normalized amplitude to change the pulse width of the optical pulses in the second modulated optical signal.

28. A method according to claim 24, further comprising varying at least one of the first normalized bias voltage and the second normalized bias voltage to achieve a predetermined extinction ratio of optical pulses in the second modulated optical signal.

29. A method according to claim 24, further comprising varying at least one of the first and the second normalized amplitude to substantially maximize the extinction ratio of optical pulses in the second modulated optical signal.

30. A system according to claim 1, wherein F1 and F2 are about 20 GHz.

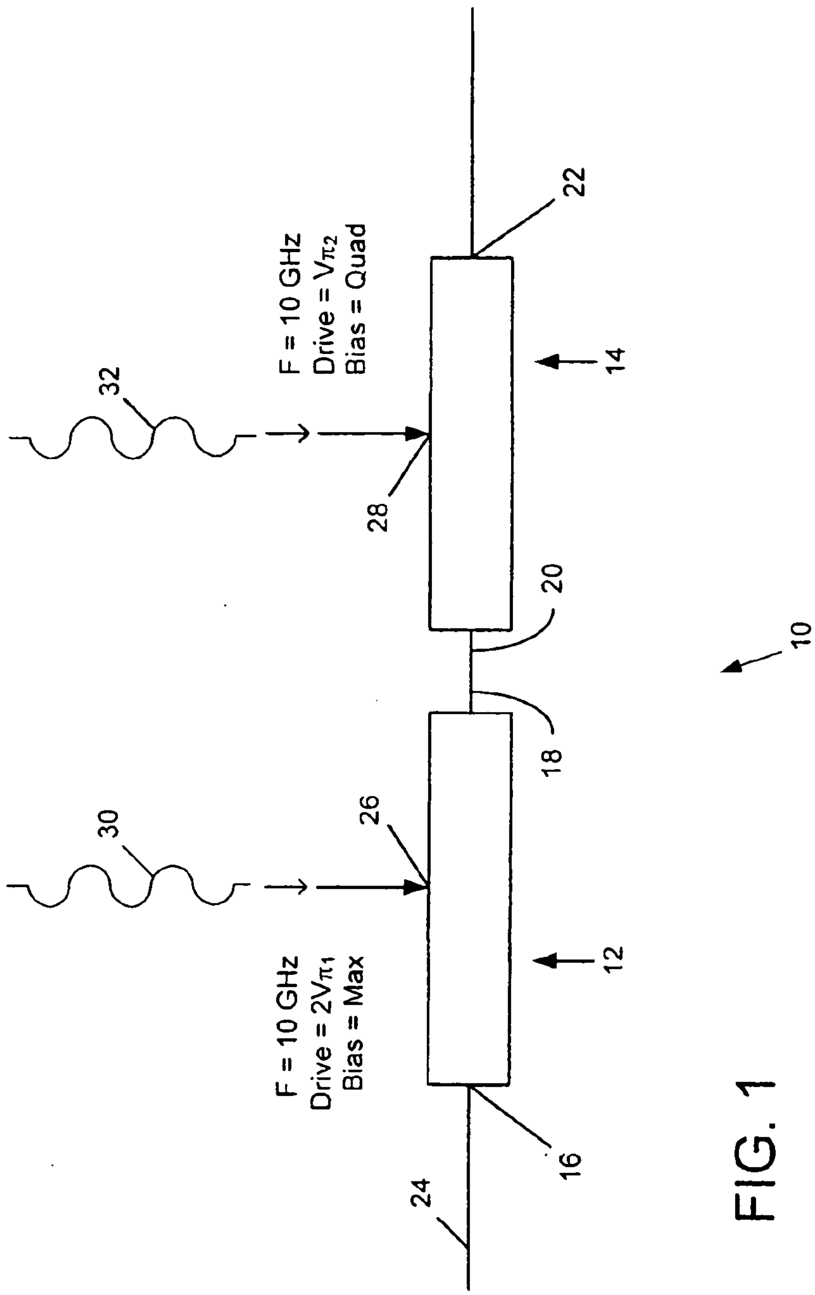

F = 10 GHz
Drive = $V_{\pi 2}$
Bias = Quad
F = 10 GHz
Drive = $2V_{\pi 1}$
Bias = Max
10
12
14
16
18
20
22
24
26
28
30
32

FIG. 1

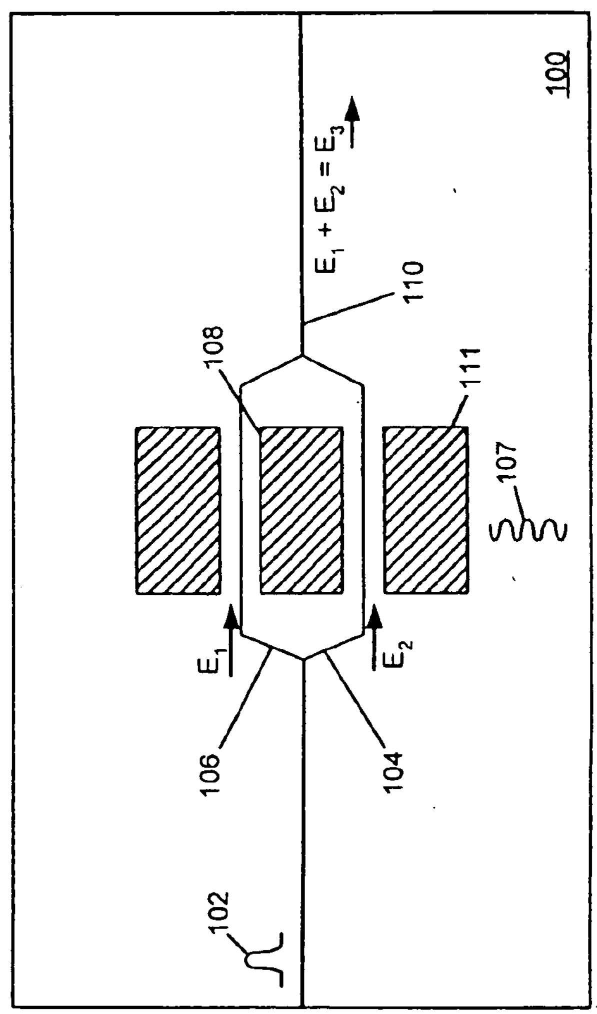


FIG. 2
(Prior Art)

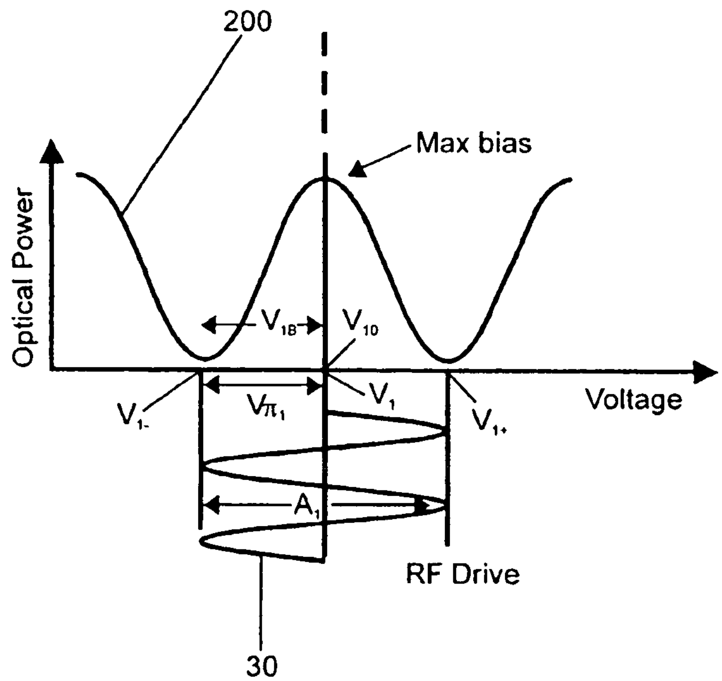

200
Max bias
Optical Power
V_{1B}
V_{10}
V_{1-}
$V\pi_1$
V_1
Voltage
V_{1+}
A_1
RF Drive
30

FIG. 3A

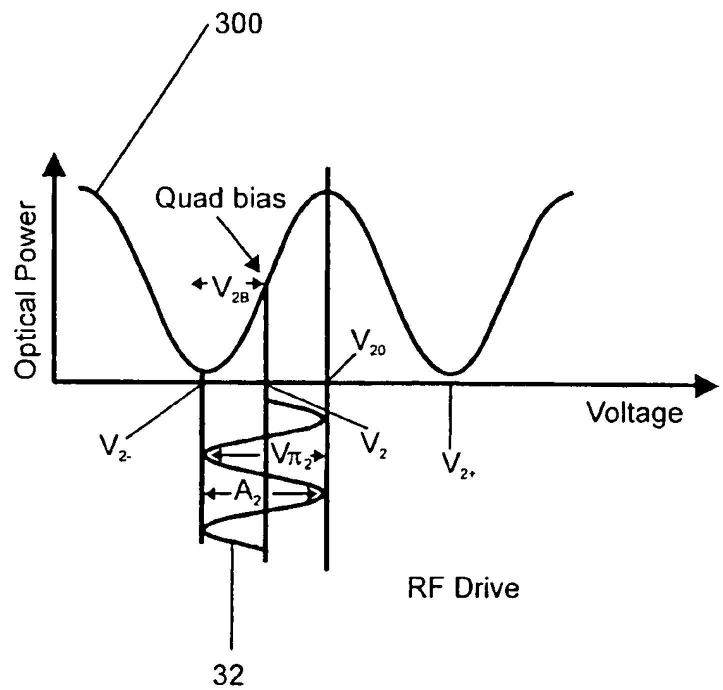

300
Quad bias
Optical Power
V_{2B}
V_{20}
Voltage
V_{2-}
V_2
V_{2+}
$V\pi_2$
A_2
RF Drive
32

FIG. 3B

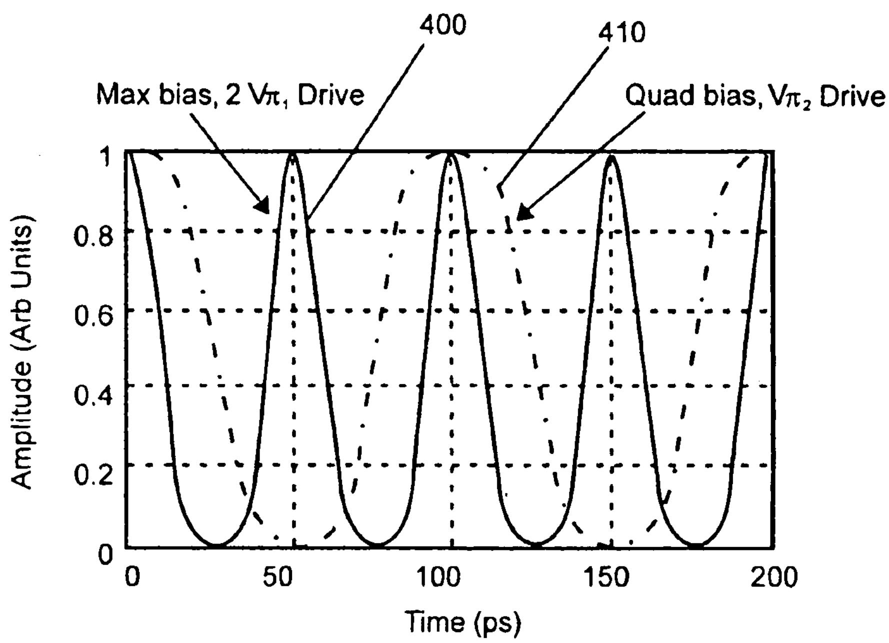
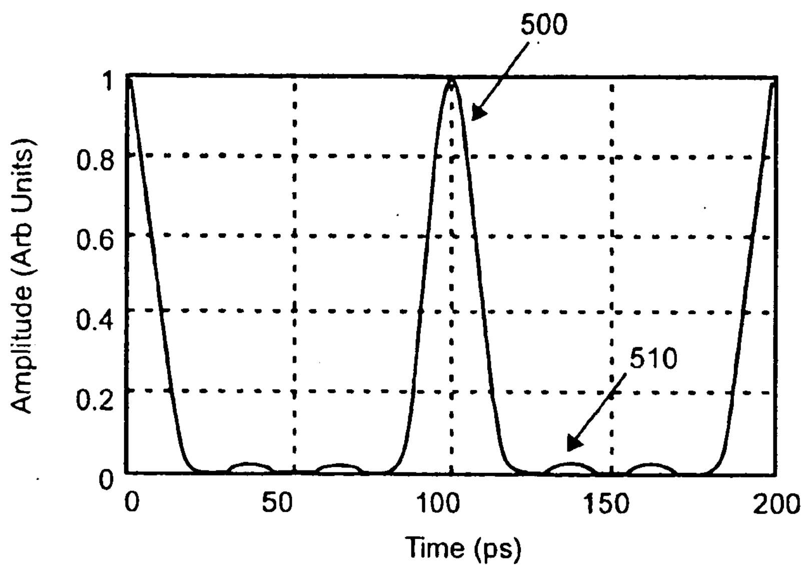

400
410
Max bias, 2 Vπ1 Drive
Quad bias, Vπ2 Drive
Amplitude (Arb Units)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
Time (ps)

FIG. 4



500
510
Amplitude (Arb Units)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
Time (ps)

FIG. 5

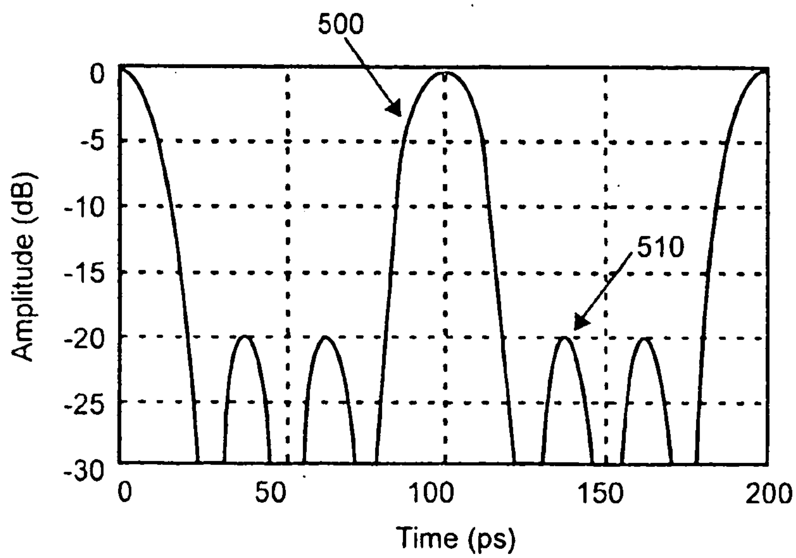


FIG. 6

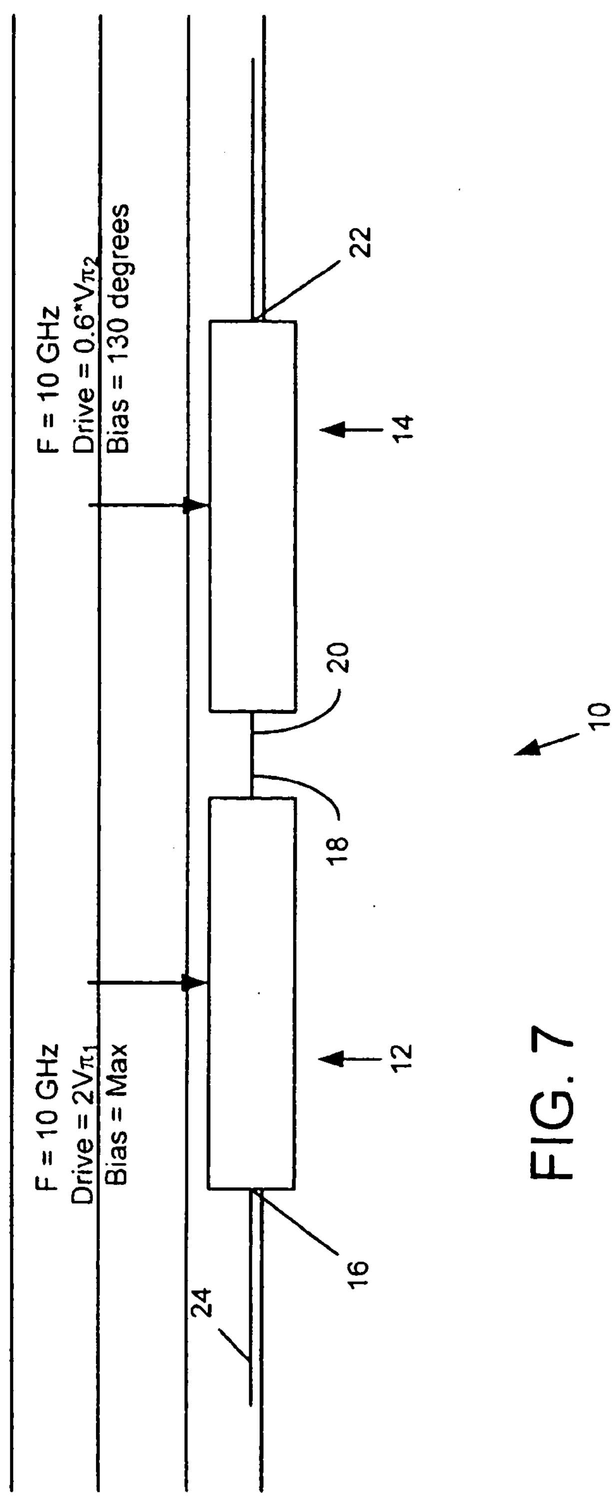

F = 10 GHz
Drive = 0.6*V_{π_2}
Bias = 130 degrees
F = 10 GHz
Drive = 2V_{π_1}
Bias = Max
22
14
20
10
18
12
16
24

FIG. 7

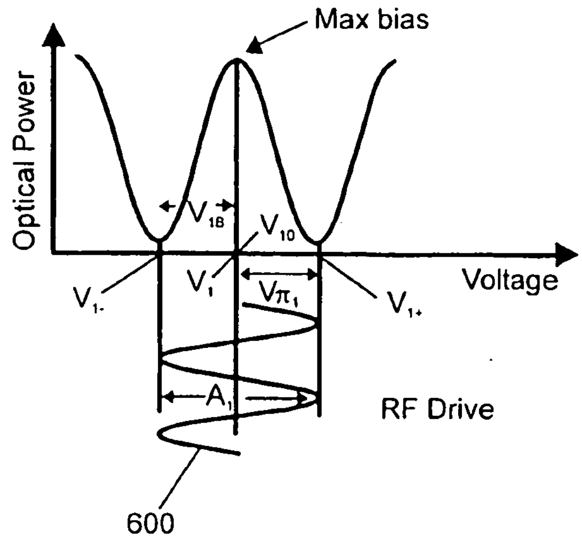

Max bias
Optical Power
V_{1B}
V_{10}
V_{1-}
V_1
$V\pi_1$
V_{1+}
Voltage
A_1
RF Drive
600

FIG. 8A

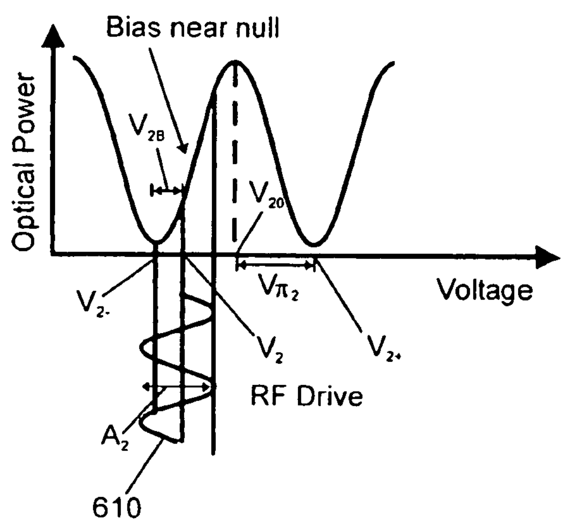

Bias near null
Optical Power
V_{2B}
V_{20}
V_{2-}
$V\pi_2$
Voltage
V_2
V_{2+}
RF Drive
A_2
610

FIG. 8B

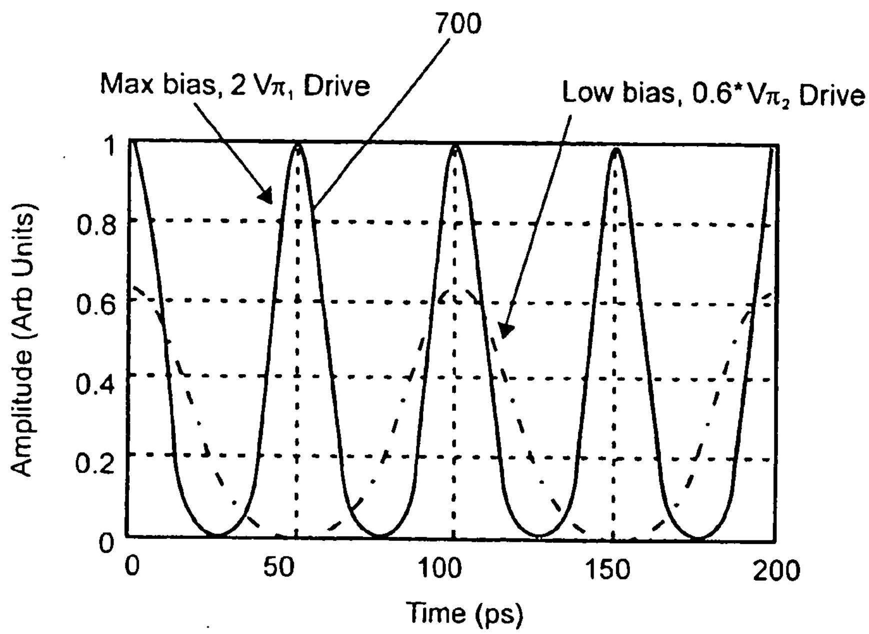

700
Max bias, 2 Vπ₁ Drive
Low bias, 0.6* Vπ₂ Drive
Amplitude (Arb Units)
1
0.8
0.6
0.4
0.2
0
0
50
100
150
200
Time (ps)

FIG. 9

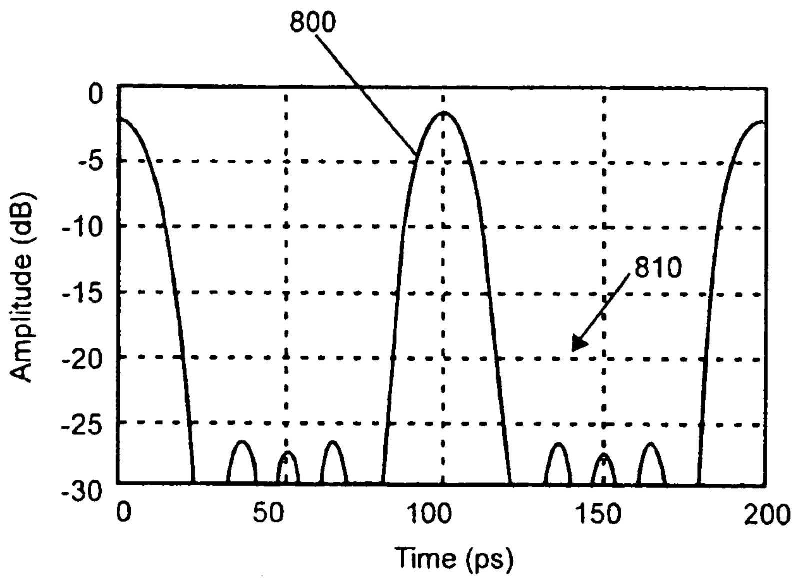


FIG. 10

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US02/23621

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G02F 1/035

US CL : 385/2

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 385/1-9,14,40,41

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO, JPO, Derwent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,148,503 A (Skeie) 15 September 1992 (15.09.1992), fig. 5	16,18-30
X	US 5,854,862 A (Skeie) 29 December 1998 (29.12.1998), fig. 8	16,18-30
A	US 5,040,865 A (Chen et al.) 20 August 1991 (20.08.1991) fig. 4	1-30
A	US 5,168,534 A (McBrien et al.) 01 December 1992 (01.12.1992) figs. 1,3	1-30
A	US 5,249,243 A (Skeie) 28 September 1993 (28.09.1993) fig. 14	1-30
A	US 5,278,923 A (Nazarathy et al.) 11 January 1994 (11.01.1994), fig. 15	1-30
A	US 5,321,543 A (Huber) 14 June 1994 (14.06.1994) fig. 2	1-30
A	US 5,422,966 A (Gopalakrishnan et al.) 06 June 1995 (06.06.1995) fig. 1	1-30

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 August 2002 (26.08.2002)	25 SEP 2002

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